LUNAR AND HAWAIIAN PHYSICAL FEATURES.

PICKERING.

With the Compliments of
the Author.

IV.

LUNAR AND HAWAIIAN PHYSICAL FEATURES COMPARED.

BY

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WITH SIXTEEN PLATES.

Presented February 9, 1906. Received April 7, 1906.

Mokuaweoweo at Night.

Compare with Figure 18 taken at about the same date.

LUNAR AND HAWAIIAN PHYSICAL FEATURES COMPARED.

THE lunar surface presents such a strong contrast to the more thickly populated portions of the Earth, that little resemblance between them can be traced. It has therefore naturally proved very difficult to explain the nature and origin of many of the features of our satellite. Even those of our volcanic regions which have been most extensively studied, show little analogy to the Moon. There are other regions, however, notably in the Hawaiian Islands, where an entirely different class of volcanic phenomena are exhibited. These it is now found bear a striking resemblance in some respects to what we find upon our satellite. Although the Hawaiian craters are mostly extinct, or at present inactive, yet they are the only ones known of this type exhibiting any activity whatever.

In view of these facts the writer determined to visit the Hawaiian Islands in the summer of 1905, and study their volcanic features with especial reference to those found upon the Moon. In Hawaii a considerable number of the craters are of the engulfment type, as distinguished from those of the explosive type, so well developed in southern Europe. In the latter class a high truncated cone is built up by mild eruptions of steam and cinders, sometimes alternating with lava. At long intervals violent explosions occur, which sometimes blow away a large portion of the summit, thus entirely changing the shape of the mountain. Such an explosion of steam occurred in Vesuvius at the time of the destruction of Pompeii, and a still more violent one in Krakatoa in 1883. Nothing whatever of this sort is found upon the Moon. In volcanoes of the engulfment type on the other hand, comparatively little steam is evolved, often there is no exterior cone, and the craters enlarge quietly by the cracking off and falling in of their walls.

The Hawaiian structures, although similar to those of the Moon, are comparatively on a very small scale, and their dimensions must often be multiplied by a factor of from 100 in the case of the older craters, to 300 in the case of the more recent ones, in order to equal the dimensions of the similar formations found upon our satellite. This applies especially to horizontal distances, — vertically a factor of from 10 to 20 more nearly represents the proper proportion.

The force of gravitation at the surface of the Moon is but one-sixth as great as it is upon the Earth, and this difference is usually given as the cause of the great comparative size of the lunar formations. On the old theory that the lunar craters were due to explosions of steam, like our explosive volcanoes, it was evident that matter expelled from a crater vent could be thrown six times as far as upon the Earth. Although this theory is now practically abandoned, gravitation would still have an influence on the relative size, since a cliff or pinnacle upon the Moon could be six times the height of one upon the Earth, and yet exert no greater crushing force on the material beneath it. Still it is very evident that this explanation alone is inadequate to account for the great difference in size actually observed.

The facts seem to be that we are really trying to compare objects formed under entirely different conditions. The larger craters on the Moon came into existence when the thin, solid crust covering the molten interior was, owing to the solidification and contraction of the crust, much too small to contain the liquid material. The craters were therefore formed by the lava bursting through the crust, and so relieving the pressure.

Later, after this relief had been found, and the crust had thickened, the interior regions by cooling shrank away from the solid shell which was now too large, and being insufficiently supported caved in, permitting the great fissure eruptions which produced the *maria*. These extensive outflows of lava dissolved the original solid shell wherever they came in contact with it much as they do at the present day in Hawaii. Had the Moon been much smaller, these extensive eruptions would not have attained such relatively great size, or might even not have occurred at all. On the other hand, had the Moon been larger, their relative size would have been greater, since the volume of the sphere would have been larger in proportion to its surface and would therefore have shrunk more in proportion. This was precisely what took place upon the Earth in all probability: our original gigantic craters were destroyed by the outflow of the earlier archaic rocks, which completely submerged and dissolved them. Our present Hawaiian craters must therefore be compared, not with the primary formations still left upon our Moon, but rather with the secondary ones formed later upon the surface of its *maria*. Of these Bessel, twelve miles in diameter, is a large and well known example. From this size down countless craterlets are known.

Three craters are found upon the Earth measuring about fifteen miles in diameter. They occur in Kamchatka, in Japan, and in the Philippines, but are all of the explosive type, and therefore not comparable to those found on the Moon. It is possible that a large engulfment crater formerly existed upon Kauai, and another in southern Hawaii, near the coast, south of Mauna Loa, but the writer was unable to examine either of these regions during his recent visit. The latter crater must have been about five miles in diameter, the former perhaps much larger. The largest engulfment crater known is Crater Lake, Oregon, measuring five by six miles in diameter, with a depth of about 3,000 feet. Next to it comes Haleakala in the Island of Maui, Hawaii, measuring seven miles in length by two in width. It is about 2,000 feet deep.

The secondary craters found upon the lunar *maria* are so small that it is impossible to study their interiors to advantage; we shall therefore content ourselves with comparing the Hawaiian formations, as far as possible with the large primary formations of the Moon, without regard to the great discrepancy in their relative size.

On the Hawaiian Islands with the exception of the three great craters of Haleakala, Mokuaweoweo, and Kilauea, few of the crater pits exceed half a mile in diameter, measured on their crater floors, or former free liquid lava surfaces, although there are probably several hundred pits over 200 feet in diameter. In addition to these are countless cinder cones, spiracles, etc. On the Earth at present the cooling process always intervenes before great size is attained. Doubtless formerly the lava was hotter when it first issued from the interior than it is now, also the solid crust resting on the liquid mass was thinner, so that the channel communicating with the interior was shorter and of greater diameter, thus offering a freer passage to the liquid flow.

Terrestrial craters may be divided into three classes, according to the materials of which they are composed. These are (a) tuff or tufa cones, which are made of hardened volcanic mud, (b) cinder cones, made of scoria, lapilli, or sand, that is, lava broken up into masses of varying size, by the action of steam, from stones several inches or even feet in diameter to fine powder, and (c) lava craters, where the lava occurs in unbroken masses. It is this third class, where less water is involved in the eruption, which most resembles what we find upon the Moon. Representatives of all three classes are to be found in Hawaii. Many volcanoes like Vesuvius eject both cinders and lava.

The third class may again be divided into four subdivisions according to the shape of the craters, namely: lava cones, lava pits, lava rings, and lava bowls. Although sometimes of small size, the lava cones often emit vast volumes of lava, which taking the form of broad streams may extend for many miles. The lava pits are by far the most numerous group, and most widely distributed throughout the islands. They have no outer slopes whatever, consisting simply of a pit sunk in the ground. Their walls are sometimes vertical, descending without talus to a flat floor; sometimes the talus is present, and may cover the whole floor, leaving the bottom as a conical pit. Sometimes the walls are inclined, descending at a uniform slope to a flat floor. The slope in this case is usually steep,—perhaps 45°. The crater rings are the rarest type, and resemble the larger craters found upon the Moon. They have flat floors and sloping inner and outer walls. The crater bowls differ from them in that the bottom instead of presenting a well-defined flattened floor is concave, the curvature being continuous with that of the walls. They are identical in appearance with most of the smaller lunar craters. Section drawings illustrating these different forms will be found on p. 171, and will be described when the various types are reached. Photographs of many of them are also given at the end of this memoir.

In addition to the craters, there are found numerous other interesting formations, such as lava caves, channels, cracks, spiracles, pinnacles, ridges, etc. A spiracle is literally a blow hole, but in this paper, for lack of a better name, I have used the word to indicate the solid formation surrounding the hole. In dealing with these various objects it has been thought best to describe each class by itself, stating where the best specimens of each may be seen.

The visitor to Hawaii, on entering the harbor of Honolulu, is at once struck with two very conspicuous volcanic formations, known as Diamond Head and the Punchbowl. Other smaller and less conspicuous craters, of the same general type, will be found in the immediate vicinity. The Punchbowl, *a*, p. 171, reaches an altitude of 498 feet, and is situated within the city limits. The crater is but slightly concave, being filled nearly to the brim, and has a diameter of 2500 feet. The writer did not have an opportunity to examine it carefully, but as it was evidently similar to Diamond Head, *b*, p. 171, which was larger, and apparently better preserved, this was not greatly regretted.

From every direction Diamond Head, Figure 1, presents an appearance similar to a lunar crater. Its highest point reaches an altitude of only 761 feet above the sea, while the diameter of the crater rim measures 3200 by 3700 feet. An ascent of the rim on foot is easily made from a point on the road just beyond the terminus of the electric car line. The rim at this point has an altitude of 450 feet. In the interior of the crater, somewhat to one side of the centre, is located a shallow lake, sometimes dry, whose bed measures 220 feet below the rim where we crossed it. It is surrounded by a very dense growth of thorny shrubs. Within the crater was found a specimen containing a fossil shell, which was doubtless brought up from the ocean bed by the erupted material when the crater was active. A branching system of cracks, none of them exceeding three inches in width, was found in one place. The inner slopes of the crater range from 20° to 45°, the outer from 30° to 70°. Clearly the walls were formerly somewhat higher, and the interior and exterior of the crater about on a level. The edge of the rim is extremely sharp in places. The material is composed of a hardened volcanic mud or tuff, and while the crater somewhat resembles numerous of the smaller lunar craterlets, yet their interiors are always at a lower level than the exterior plane on which they are situated, and their inner slopes are steeper than their outer ones. The crater seems to offer little analogy therefore to the formations upon the Moon.

Cinder cones, *c* p. 171, form the most numerous class of craters in Hawaii. They are found scattered over the summit of Mauna Kea, in the valley between Mauna Kea and Mauna Loa, in the interior of Haleakala, along the southern and northwestern coasts of Hawaii, and in many other places. A group situated near the summit of Mauna Kea is shown in Figure 2. They have all the characteristics of explosive volcanoes like Vesuvius, although their craters are larger in proportion to the height of their cones. So far as is known they bear no analogy to anything found upon the Moon.

The third class, or lava craters, on the other hand, present a close resemblance in many respects to some of the lunar formations, and we shall therefore describe them in detail. The first subdivision, the lava cones, are most strikingly represented by Mauna Loa, by far the world's largest volcano. It and Mauna Kea are also our highest mountains if we measure in every case from the mountain's base. For the Hawaiian volcanoes the base lies 15,000 feet below the level of the sea. Nevertheless, the summit crater of Mauna Loa is so large in proportion to its depth that it was thought best to select a small lava cone in Haleakala as the typical example of this form of crater. This cone is shown in the right foreground of Figure 3, and its section at *e* on p. 171. The outer slopes of a lava cone are often covered by loose cinders, as in the present case, and the inner slopes may be inclined like those of a cinder cone, although they are generally much steeper, but if the inner walls are of lava its classification is assured. Lava sometimes issues from the summits of these cones, but sometimes it comes directly out of the ground, as in Kilauea Iki and at Huehue, — no trace of a cone being found.

Lava has not been known within historic times to overflow the summit crater of Mauna Loa, but it escapes from just below the summit, outside the crater walls, in enormous quantities, especially upon the northeastern side. The vast bulk of the mountain seems to have been built up largely from these emissions, and the same is true also of Mt. Etna in Sicily. It is characteristic of these mountains that their slopes are much more gentle than those of cinder cones, and this is especially true of Mauna Loa, Figure 4. The summit of this mountain is 13,675 feet in elevation. The view was taken from the north, and represents the upper 7000 feet of the mountain. The summit is very difficult of access on account of the exceedingly rough nature of the ground, the total absence of water, and on account of its flatness of the long distance of the summit from a base of supplies. It is probably best reached from the Kona, or western side, by way of Kealakekua Bay.

The slopes of Etna are heavily buttressed by ridges, formed each of a separate lava stream, which has flowed from the small lava cones upon the flanks of the mountain. This structure is also well shown in the lunar crater Bullialdus, Figure 5. The diameter of this crater is 38 miles. Since these streams sometimes cross one another, leaving diamond-shaped hollows between them, it is obvious that the formation cannot be due to the grooving of a smooth surface by erosion, but must really be formed by projecting ridges. We shall refer again to this matter in connection with Clavius and Kilauea Iki. We thus have indirect evidence of the existence of lava cones upon the Moon, as the source of these streams.

Until recently this was all the evidence we had. The tall volcanic cone with the comparatively minute crater at its summit, so characteristic of the typical terrestrial volcano, was supposed to be absent from the Moon. In the terrestrial volcano the floor of the crater is always higher than its base; on the Moon the reverse is true. A recent examination of a lunar photograph taken at the Yerkes Observatory by Professor Ritchey has shown, however, that the terrestrial type of volcano is not wholly absent from the Moon. Craters of this type have not been found before, merely because, like those on the Earth, they are very small. Figure 6 represents the two craters Kies and Mercator. Between them is seen a comparatively small cone with a minute crater upon its summit. It proves to be nine miles in diameter at its base, and 2000 feet in height, while the crater itself measures half a mile in diameter. For purposes of comparison we may say that the diameter of the base of Vesuvius, including Monte Somma, is eight miles, and its height 4000 feet. The diameter of its crater, which varies with every eruption, rarely exceeds one quarter of a mile, and is sometimes but a few hundred feet. The mean angle of the slope of Vesuvius is $10^\circ.7$, that of Etna $7^\circ.6$, of Mauna Loa $5^\circ.1$, and of the lunar cone $4^\circ.8$. Vesuvius is partly a lava and partly a cinder cone, which accounts for its steepness. If it were purely a cinder cone its angle might rise to 20° or even 30°. Etna and Mauna Loa are both lava cones, the lava of the latter being more fusible. We may infer that the lunar cone is composed of similar material. It is probable that other similar lava cones exist upon the Moon, and one is suspected lying six-tenths way from Copernicus to Kepler, and a little to the north.

Lunar photographs are usually oriented with south at the top. The right hand side is called east. Figures 14, 15, 31, and 35 were taken with a telescope of long focus, using an aperture of six inches, at the Harvard Station in the Island of Jamaica. The remaining lunar photographs were copied from lantern slides from photographs made by Professor Ritchey at the Yerkes Observatory. In Figure 5, one diameter to the south, and a little to the east of Bullialdus is a pair of coneless lava pits, the southwestern one being much the larger of the two. A few other very minute pits are shown upon the photograph, but all the larger ones have cones. In Figure 29, in the upper left-hand corner, five small craters are shown in a line running north and south. The northern one, which is also the smallest, is coneless. One slightly larger than this, also coneless, is shown just above the centre of the picture, on the southern side of the great rill. It measures five miles in diameter. These seem to be true engulfment craters, as distinguished from the expulsion craters hitherto described. Similar lava pits are found to the west and northwest of Copernicus, and also upon the Oceanus Procellarum. In general they are very minute objects. No large crater pits are known.

In Figure 7 we have a small terrestrial crater of this type. It is known as Kauhaku, and is found on the island of Molokai. It has no exterior cone whatever, and is merely a hole in the ground. Even explosive craters start in this form, the cone being formed immediately of materials ejected from the hole. Coneless engulfment craters abound on the slopes of Hualalai. See *k*, *l*, *m*, and *p*, p. 171. Many are also found to the southeast and east of Kilauea, but the best known of all is Halemaumau, on the floor of Kilauea itself, *d*, p. 171. Figure 8 is known as Kuuohi, or more familiarly as the sixth crater, and is situated six miles to the southeast of Kilauea. See also *f*, p. 171. The floor of the main crater pit measures about 6,000 feet in length by 2,000 in breadth. Its depth below the surrounding surface is 400 feet. At its eastern end a second crater pit has formed. This measures 2,000 feet in diameter, and has an additional depth of 600 feet. It furnishes a vertical section, 150 feet in depth of the primary floor, below which the walls form an inverted truncated cone to a small floor a few hundred feet in diameter. The lava of the upper twenty-five feet of the vertical section has a horizontal stratification, and is clearly distinguished from the portion below it.

Of the three great Hawaiian representatives of the engulfment type, Mokuaweoweo, the summit crater of Mauna Loa, Figure 9, and Kilauea, Figure 10, are coneless, while Haleakala, Figure 3, has in places a well-defined outer slope. This might lead us to suspect that it was of composite origin, an impression that is further confirmed by the fact that both its inner and outer slopes are made up in part of lava, and in part of scoria and sand. It seems to have originated partly by the engulfment process and partly by explosions of steam.

No evidence of the great crater of Mokuaweoweo is to be seen until just before we reach its rim. It measures 3.7 by 1.7 miles in diameter, and is 300 to 400 feet in depth. It is composed of three confluent craters, of which the middle one is much the largest. A portion of the two northern ones is shown in the figure, the view being taken in a direction nearly due south. The crater floor corresponds very closely in its nature to a lunar *mare.*

Kilauea is much more accessible than Mokuaweoweo. Twenty-two miles in the train from Hilo, and nine miles by stage brings us to the Volcano House, situated upon its brink. Kilauea consists of a black lava plain measuring two miles by three, bounded on all sides by precipices, often vertical, ranging from 200 to 500 feet in height. The view, Figure 10, was taken from its southeastern rim looking north. It is a curious fact that the black lava usually shows in the photographs to be much lighter colored than the gray cliffs surrounding it. Since the whole lava surface is very irregular, the fact that it is shiny and therefore bright in spots, cannot be given as an explanation of this fact. The surface is distinctly convex, *d* p. 171, as is the case with the smooth crater floors upon the Moon, and is not unlike in shape and curvature to the flattened summit of Mauna Loa, Figure 4. *A* in the section indicates the location of the Volcano House. The line *B* is on a level with it. The highest part of the floor is near Halemaumau, and in 1905 measured 230 feet above the edge where the Volcano House trail strikes it. The edge is 410 feet below the Volcano House at this point.

Halemaumau, " the house of eternal fire," is situated three-quarters way across the crater from the Volcano House. It is at present a nearly circular pit, 2,000 feet in diameter, with practically vertical sides, and when the writer was there early in August its depth was estimated at 500 feet. Its floor consisted of a comparatively smooth lava surface, crossed here and there by narrow cracks, which at night showed bright red. That it was liquid only a few inches below the surface was shown by an occasional outbreak, when a flow of lava 5 to 10 feet broad by 20 to 50 feet in length would sluggishly stretch itself across the floor, glow for a few minutes, and then cool and solidify. From a height of 500 feet the phenomenon presented little of interest compared to what had been seen in the last century. The crater is gradually filling up from a subterranean inlet. The depth of the pit in 1902 was estimated at 1,000 feet. The lower portion, which has now been filled was then conical in shape.

Turning now to the third subdivision of the lava craters, the crater rings, we will begin by a study of what is believed to be their internal structure, as exhibited in Figure 11. This photograph represents a vertical section of a small ring crater formed naturally in cooling iron slag. When the slag is drawn off from the furnace it is allowed to solidify in conical moulds four or five feet in diameter, and about a foot in depth at the centre. Unless interfered with, a crater three or four inches in diameter is invariably formed as soon as the surface has fairly hardened. On breaking up the slag considerable cavities are always found beneath the crater. These are well shown in the figure, as are also the cracks connecting them with one another and with the central peak, which it will be noted is also hollow. The large pear-shaped cavity beneath the peak was in the present instance filled up from below with melted iron. It will be noted that the inner walls are very steep, while the outer ones slope more gradually. During the process of formation the crater sometimes fills to the brim and overflows, building up the walls; later the interior fluid withdraws, forming the crater floor.

Besides these larger craters other ones are often formed, which, while retaining a base of perhaps two inches in diameter, frequently build up to the height of several inches, forming vertical tubes or spiracles. Sometimes these tubes are closed at the top and sometimes they are left open. For these facts, and for the specimen from which Figure 11 is taken, I am indebted to Mr. J. A. Brashear.

Halemaumau, known also as "the pit," is the centre of volcanic activity in Kilauea. No eruption has ever been known to overflow the walls of the latter, although lava has sometimes been emitted from cracks located high up on its sides. When the pit of Halemaumau is emptied, it is always through some subterranean passage, occasionally reaching the surface, but usually either filling some subterranean cavity, or else discharging beneath the sea. These eruptions, though often accompanied by slight earthquake shocks, have in only one instance caused serious damage and loss of life. In this case it is thought that the active agency was really Mauna Loa, whose eruption took place at the same time.

When Halemaumau is really active the sight is said to be grand beyond description, especially at night. Lakes of liquid lava occur both within and without it. Numerous fire fountains from ten to fifty feet in height play over the surface of these lakes.

At times the surface solidifies, then suddenly a crack will run across it, and in a few minutes the whole solid material will break up into separate cakes which will presently turn on edge and sink beneath the surface of the lake. This again solidifies, and in a few hours the process is repeated. See report of the United States Geological Survey for 1883, p. 106, Major C. E. Dutton.

These lakes are especially interesting to the selenographer, since about them are formed crater rings, which seem to be analogous in appearance to the larger crater formations upon the Moon. During the past forty years, since the construction of the hotel upon the rim of Kilauea, they have been very carefully observed, and it will therefore be well in this place to deal with the subject, briefly, from the chronological standpoint. All the earlier descriptions which follow are condensed from the writings of the Rev. Titus Coan. The references given refer to the American Journal of Science.

On April 2, 1868, a severe earthquake shook the southern coast of Hawaii, and for the next five days a subterranean discharge of lava took place from Kilauea. As a result of this discharge the central area to the northeast of Halemaumau sank about 300 feet, carrying with it the vegetation still growing on its surface. The walls of this new pit were inclined from 30° to 60°. The lava also flowed out of Halemaumau, leaving a circular pit 3000 feet in diameter at the top, 1500 feet at the bottom, and 500 feet deep. Its walls were in some places vertical, and in some slightly overhanging. A. J. S., XCVII, 96. In A. J. S., CXVIII, 227, it is stated that the depth was 400 feet and that the distance across the bottom was one mile less one hundred feet. It is also stated that the pit had formerly been filled up not only from the bottom, but by lateral discharges from the walls.

A year later Halemaumau had filled to within 100 feet of the top, the level area within it showing eight small apertures within which the liquid lava could be seen boiling fiercely 50 to 100 feet below the surface. A few months later the lava was within 25 feet of the rim, and the diameter of the pit was said to have enlarged to over a mile. A. J. S., XCIX, 393.

In 1870 the pit overflowed, the lava pouring down and partly filling the northeastern depression. At the time of an eruption such as this, the lava rises, overflows and cools, thus forming a raised rim or circular dam. Such a rim is shown on a small scale in the slag crater, Figure 11, and on a much larger scale in the photographs of Halemaumau, Figures 12 and 13, the cakes of lava there represented appearing much like broken cakes of ice. In Figure 14 is shown a portion of the Moon near the limb, so as to present the craters obliquely. It will be noted that the two large craters there represented, named Schickard and Phocylides, both present a form similar to the crater rings of Halemaumau. The chief one, Schickard, measures 134 miles in diameter. All of the larger craters on the Moon are of this type. When seen towards the centre of the disc, however, their depth appears by an optical illusion greatly exaggerated. Thus Clavius, the largest crater shown in Figure 16 measures 143 miles in diameter, and judging by appearances only might be 15 to 20 miles in depth. Its depth actually measures two and a half miles, or about the same as the diameter of one of the most minute craterlets visible in its interior. The slope of its eastern inner wall is about 10°.

There is another crater known as Wargentin, lying between Schickard and Phocylides and the limb, Figure 14. It is not shown in the photograph because it is a very difficult object. This is not on account of its size, since it measures fifty-four miles in diameter, but because it has no interior depression. In this respect it has heretofore been thought to be unique upon the Moon. That such is not the case, however, an inspection of Figure 32 will show. Near the upper edge of the figure a large low nameless crater is to be seen whose interior is obviously at a greater elevation than its exterior, although the difference is not as great as in the case of Wargentin. It measures about fifteen miles in diameter. In each of these cases the lava passage leading to the interior of the crater evidently became choked while the crater was still brimful of molten matter, thus preventing the withdrawal of the lava, and preserving the crater as a permanent illustration of the method by which these formations are produced.

The outside height of the crater rings in Halemaumau rarely exceeds 15 to 25 feet. The inside height is constantly varying with the fluctuating level of the surface of the lava lake. When the outside height becomes too great to withstand the internal pressure, the rim gives way, and the lava breaks through and floods the surrounding regions. By means of this successive building up and flooding, the whole region around Halemaumau was elevated, until the walls became too high and too thick for the floods to escape over or through them. The pit at this time measured a mile by a mile and a half, and was 700 feet in depth. Since the lava could not now overflow the rim, it escaped by subterranean passages, and thus flooded the other portions of the floor of Kilauea. A. J. S., CII, 454.

It is doubtful if the walls of the pit were raised exclusively by the process thus explained by Mr. Coan. It is probable that the whole of this portion of the floor was also elevated as one piece by the pressure of the subterranean lava, as occurred in the later eruptions.

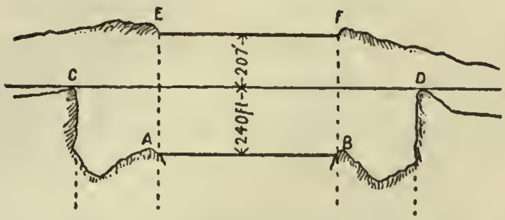
On the Moon the height of the outer wall is roughly proportional to the diameter of the crater. For a crater whose diameter measures 30 to 40 miles, the height of the outer wall is usually about one mile. For a crater a mile in diameter its height would be 150 feet. Dividing this figure by 6, the correction for gravity mentioned at the beginning of this paper, we find 25 feet to be the theoretical height for a terrestrial crater a mile in diameter, thus agreeing with the figure above given.

In April, 1879 a silent discharge from the crater occurred, the lava apparently making its escape out at sea. A few months later activity was again resumed, the crater becoming extremely active in 1880. A. J. S., CXVIII, 227; CXX, 72.

On March 6, 1886, Halemaumau was again emptied. It was a silent discharge like its predecessor. For several days the surrounding walls continued to fall into the pit. A month later the deepest portion had the shape of an inverted cone, whose apex was 570 feet below the floor of Kilauea. Three months after an erect cone was found formed of loose blocks, and measuring 150 feet in height. During the next two years this cone gradually floated upwards, no additions being made to its summit. This action seems to have been due to the pressure of the lava beneath it. The rate of elevation was about three inches per day. A. J. S., CXXXI, 397; CXXXVII, 48.

The next discharge of Halemaumau occurred on March 6, 1891. It was accompanied and followed by a series of light earthquake shocks, but otherwise it was a quiet discharge. Prior to this date the pit contained a central cone with three lakes surrounding it, one east, one west, and one south. The direction of the current on the surface of these lakes in each case was away from the cone. The cone which consisted in part of several peaks rose to a height of at least 200 feet above the lakes. As seen from the Volcano House about one-third of its height was above the western wall of Kilauea. The structure of these peaks was loose, and sulphurous vapors escaped from their whole surface. The fire fountains on the lakes sometimes played obliquely, and without the emission of steam. On the evening of March 6, at 9:30, a light earthquake shock was felt, and the peaks settled slightly; the next morning they were out of sight. A month later in place of the peaks and lakes an empty pit was seen, measuring half a mile in diameter. The walls were vertical and 500 feet in depth. Soon after this the lava reappeared in the bottom of the pit, and by the end of April a lava lake 100 to 200 feet in diameter had formed. A year later the diameter of the lake was a little over 800 feet. It was then very active, as many as fifteen fire fountains having been counted at one time. It was probably at about this time that the photographs shown in Figures 12 and 13 were taken. A. J. S., CXLI, 336, 507; CXLII, 77; CXLV, 241.

The next discharge was on July 11, 1894. In August, 1892, the edge of the pit of Halemaumau was 282 feet below the level of the Volcano House. The surface of the lake was 240 feet below the edge, 522 feet in all. (See cut.) In March, 1894, the surface of the lake was 75 feet below the Volcano House, making a total rise of 447 feet in nineteen months, or about ten inches per day. In 1892 the lake was in the bottom of the pit.



In 1894 the pit was filled, and the lake was on the top of a flat hill covering the pit and situated 207 feet above its former rim. The pit was filled partly by overflows from the lake, and partly by a rise of the whole bottom of the pit. The lake now measured 800 by 1200 feet.

On March 21 an area measuring 400 by 800 feet, situated on the northern bank of the lake, was suddenly elevated eighty feet above the other banks. The raised area was much shattered. It subsequently sank gradually, until on July 11 it again reached its former level. On that date the lava in the lake began rapidly to sink, and the walls about the lake to crack off and fall into it. The lava sank at the rate of twenty feet an hour until eight that evening. From noon till eight there was scarcely a moment when the crash of the falling blocks was not heard. A number of times a section 200 to 500 feet long, 100 to 200 feet high, and 20 to 30 feet thick would drop with a tremendous roar into the boiling lava. Such a section would form for a time a floating island in the lake, but would subsequently dissolve and sink. The grandeur and magnificence of the scene at night were indescribable. Meanwhile the fountains in the lake continued to play as if nothing unusual were happening. Only a few slight earthquakes accompanied this discharge. A. J. S., CXLVIII, 338.

Since this time for an interval of over twelve years the volcanic forces in Kilauea have been practically quiescent. There was a slight display of activity in 1896, and again in 1897, but the pit remained empty, and no activity whatever has been seen since then, except for the gradual and uneventful filling of the pit which seems now to be taking place. No such protracted interval of quiet has been known heretofore, the longest previous period amounting to only a few months. It is of interest to note that of the five recorded discharges, four occurred during the rainy months of March and April.

From these descriptions we can obtain an idea of how the lunar craters were formed, and can also account for the flat-topped vertical cliffs that we find about some of the *maria*, as in the case of Sinus Iridum, Figure 15. The walls of Mokuaweoweo or of Kilauea, Figures 9 and 10, furnish excellent illustrations of these formations. Examples of the crater rings themselves, however, are rare. The best preserved one that we were able to visit was found on Hualalai, at an elevation of 400 feet below the summit of the mountain, and was reached a few minutes after passing the so-called Bottomless Pit. It was located on the floor of a crater some 500 feet in diameter by 100 feet in depth, *g* p. 171. The diameter of the crater ring was 120 feet, its internal depth was six feet and the height of its outside wall twelve to sixteen feet. It is shown upon a larger scale at *h* p. 171. Near the centre of the outer crater, and outside of the crater ring, was a low peak. What appeared to be another crater ring was seen from the distance of a mile on the northern slopes of Mauna Loa, and will be described later. A portion of one of the crater rings formed by Halemaumau is still to be seen on the rim near the view-point where visitors look down into the interior.

The reason that these crater rings are so numerous upon the Moon and so rare upon the Earth is apparently that the terrestrial ones are not generally permanent. The smaller craters on the Moon do not take this form, and if some of them did exist formerly they have since been destroyed. The reason of this is that when the lava recedes into the bottom of the pit, the depth is so great in proportion to the diameter, that the walls cave in, destroying the ring, — as usually happens at Halemaumau. On the Moon no crater is known whose depth exceeds five miles, and two miles is the usual depth for large craters. This distance compared to a diameter of twenty to sixty miles is so slight that the ring remains uninjured. The outer walls of Haleakala may in part be the remains of an old crater ring of very elliptical shape. They have been breached and totally destroyed in two places.

The floors of the craters on the Moon are of three kinds, either they are furnished with a central peak, like Tycho, the large crater in the lower left hand corner of Figure 16, or they contain one or more smaller craters, in general not central, like Clavius, in the same figure; or they are without conspicuous detail, like Kies, Figure 6. In the last two cases the floor is often of a later origin than the walls, as indicated by its color and smoothness, the original floor having been melted by a flood of dark colored lava from below, which dissolved all the lowermost portions of the solid crust with which it came in contact. This seems to be the case with Longomontanus, the large crater northeast of Clavius. Its diameter is ninety-one miles. Often, however, the floor is bright, and not perfectly smooth, as in Tycho, showing it to be part of the original formation. Central peaks are occasionally, but by no means universally, found upon these original floors. Indeed they rarely occur in craters of less than four miles in diameter. Longomontanus and another crater known as Pitatus present the very unusual phenomena of eccentric internal peaks. Equally striking is the fact that in each case the peak is found in connection with a dark floor. The explanation in both cases is probably that the lava, after dissolving the original floor, had begun to dissolve the peaks, which were pushed by the lava currents to one side, where cooling and solidification set in before the process was completed. In both these cases the peaks are unusually small in proportion to the size of the craters, as would naturally be the case if they had been floating partially submerged in the lava.

Central peaks are seldom found in the Hawaiian craters, probably because the latter are so small. The best illustration seen was that of the small crater already mentioned at the northern base of Mauna Loa, about eight miles west of the Humuula sheep ranch, *i* p. 171. Unfortunately we could not get within a mile of it, but it seemed to be well defined. Its diameter was thought to be about 450 feet. The walls were red, and the central peak dark brown. The height of the peak was the same as that of the walls. Another small crater two or three hundred yards back of Mr. Maguire's at Huehue in Kona showed a smooth central peak 15 feet in height. It was completely grass grown. One or two of the small craters on Hualalai, *k* p. 171, showed the same formation. The peaks were never pointed, but sandy and rounded as in the slag crater shown in Figure 11. A crater containing a central peak or craterlet is said to exist half a mile beyond the sixth crater near Kilauea. Near the centre of Haleakala is found a straight, narrow ridge, 150 feet in height by 400 feet in length, along its crest. Its sides slope at an angle of about 30° and it is composed apparently of gravel and scoria. At its eastern base is the cave where parties sometimes pass the night. Although not especially conspicuous among the crater cones which dot the floor, some of which are 500 feet in height (see Figure 3), it seems to be unique in shape, running lengthwise of the crater. It is also almost exactly central in position. In passing it may be stated that the maps of Haleakala give a very erroneous impression of the shape of its floor. The floor at the Koolau and Kaupo gaps falls off sharply, showing the outline of the true floor to be not S-shaped, but elliptical, and extending nearly due east and west. It is an ellipse of great eccentricity, the length of the floor being about four times its breadth.

Figure 18 represents a portion of the middle crater of Mokuaweoweo. Somewhat nearer than the centre is shown an active cinder cone composed apparently of a medium-sized crater and two or three smaller ones upon its rim. We were not able to visit it. Like the craterlets found in Haleakala, it reminds us of those found in

Clavius. The photograph was taken in 1903 by Mr. C. W. Baldwin, and was forwarded to me through the kindness of Professor W. D. Alexander.

One of the most interesting craters that we visited was Kilauea Iki, or little Kilauea. It is situated about a mile from the Volcano House. The floor is level, one-quarter of a mile in diameter and 750 feet below the rim. The walls are very steep, but can be descended in certain places with care. Numerous small craterlets are scattered irregularly over the floor. The most complete of these is shown in Figure 19. Its height was 15 feet, and the diameter of the rim, which was composed of lava of a somewhat ropy appearance, 25 feet. A stream of lava had poured from the summit, but did not get far beyond the rim. There may have been as many as fifty rudimentary craterlets scattered over the floor, in all stages of growth, from a hardly noticeable elevation to the complete craterlet shown in the figure.

The process of construction was clearly shown, and was probably identical with that which produced Halemaumau, and Kilauea itself in the first place. In Figure 20 the top of one of the other craterlets is represented in the foreground. It was taken near at hand from the summit of the first one, and its development is clearly incomplete. The surface of the crater floor of Kilauea Iki seems to have solidified into a layer six to ten inches in depth and distinct from the portions below it, much as in the case of the sixth crater, Figure 8. A liquid core forced up from below raised this surface layer locally, and shattered it into separate pieces like cakes of ice. This core in the case of some of the smaller craterlets was sometimes only two or three feet in diameter, and could be seen beneath the shattered surface. In one instance its summit seemed to have an almost globular form, five feet in diameter.

If the volcanic forces beneath these craterlets had been more intense, it is probable that the issuing lava would have completely destroyed them, forming a series of crater pits, into which the lava would have subsequently retreated. In the south-eastern part of the floor two such pits were found, perhaps 15 feet in depth by 30 in diameter, down into which a stream of lava had poured, but had solidified without filling them up. One of these pits is shown in Figure 21. Figures 20 and 19 therefore illustrate the earliest stages of formation of a lunar crater. No other example in Hawaii is known to the writer which shows as satisfactorily as this the irregular distribution of craterlets over a crater floor.

A low ridge due to compression, caused by the sinking of the convex surface crosses the eastern end of the crater floor. Similar ridges are seen on some of the lunar *maria*, notably on Serenitatis, Figure 17. Two short, clearly marked ridges project onto the southern side of the floor of Kilauea Iki, caused by lava streams which had descended from the crater wall. They resemble similarly located formations found in the lunar crater Plato. In Clavius, Figure 16, similar ridges are seen projecting from the outer slopes of the two chief craterlets upon the northern and southern walls. Similar ridges, although much more complicated in structure on account of their numbers, have already been described in Bullialdus, Figure 5.

Leaving the craterlets and ridges of Kilauea Iki, and proceeding along a defile towards Kilauea itself, three successive lava dams were reached, each of which had served to hold back a small lava lake. In construction they were similar to the circular one represented in Figure 12, except that they were straight, and merely stretched across the defile. The first lake measured 400 feet in length by 150 in breadth. The second dam rose eight feet above its surface, and three feet above that of the second lake. By the side of this lake a core of lava of the most brilliant colors — red, yellow, brown, and purple — had escaped from the ground, and from it a black lava stream had descended to the surface of Kilauea Iki, 200 feet below. A similar core but without the colors was seen at Huehue. Both these flows occurred during the last century. Both were small, and in neither case did a cone appear, the lava issuing directly from the ground.

The fourth subdivision of the lava craters, described earlier as crater bowls, is illustrated in Hawaii by what is known as Aloi, or the Third Crater, near Kilauea. Other illustrations are found on the slopes of Hualalai. A crater near the summit, *j*, p. 171, was estimated at 800 feet in diameter by 200 in depth. The sloping walls were of lava, and the bottom of sand. The comparatively shelving outer walls probably did not exceed 100 feet in height. A portion of the interior of this crater is shown in Figure 22. A somewhat larger crater bowl with much steeper walls is found on the summit. With favorable definition such a crater would be readily seen upon the Moon, and could not be distinguished in any way from many others found there.

The largest craters on Hualalai occurred near the summit, and shortly before reaching the top we crossed a lava field strongly resembling a small lunar *mare*. A far larger number of craters are found on this mountain than on any of the others, more perhaps than on all the others combined. The three types, of cinder cones, pits, and bowls, are each represented by numerous examples. One of the craters that we passed after leaving the summit, *k*, p. 171, had sloping walls and a flat floor with sand hills on the bottom. One of these was twenty feet in height. Near the base of the walls was an inner terrace extending all around the crater. This feature of a single, well marked, inner terrace is conspicuous in a considerable number of the lunar craters, such as Fabricius, Hercules, Manilius, Reinhold, and Bullialdus (see Figure 5).

Some of the lava pits occur very near together, the intermediate wall being only a few yards in thickness, but we saw none which actually intersected. When the large summit crater was formed a smaller one near it was partially destroyed, and filled by the erupted material from the larger crater.

We have no description of the method of formation of a crater bowl, but a study of the various sections on p. 171 will show how they have probably been formed, Starting with a crater ring such as is shown in Figure 19, and in section at *h*, p. 171, when the lava retreats a crater pit will be formed within it. If the pit is very deep relatively to the diameter of the ring, the latter will be destroyed, and we shall have simply an ordinary pit, *l*. If the pit is not so deep relatively to the diameter of the rim the latter may be preserved, *n*. The floor of the pit may be flat, or it may sink towards the centre, *m*. If the pit is on a large scale the sides are less liable to be vertical, and moreover a talus will collect at their base, *o*. This will gradually become rounded as at *p*, or if the crater ring is still left, as at *j*. The flattened floors of the larger craters on the Moon are illustrated by *g*, while the terrace and central peak are shown at *k*.

With the exception of the crater pits, nearly all the smaller depressions upon the Moon are crater bowls, and they outnumber at least ten times all the other depressions put together. The smallest crater rings are about five miles in diameter. One of the largest and best situated crater bowls is Triesnecker, 14 miles in diameter. It has an inconspicuous central peak. In the smaller bowls this feature seems to be lacking. A well-graduated series of bowls is shown in the interior of Clavius, Figure 16. The process which converts a pit *l* into a bowl *p* upon the Earth is due chiefly to the action of water. Upon the Moon, even in former times, water was probably scarce, but owing to the extremely rarefied atmosphere the extremes of temperature are excessive. A range of 300° C. or 540° F. occurs every fortnight, and it seems likely that a considerable destruction of ridges and filling of hollows would be due to this cause by itself.

Another explanation of crater bowls is given by Gilbert in his dissertation on "The Moon's Face," Philosophical Society of Washington, Bulletin XII, 251, where he suggests that they may be due to a single explosion of steam, like the terrestrial "maars." This seems improbable, since volcanic features due to steam are notably absent from the Moon. On Hualalai the crater bowls have smooth lava walls which are not at all fragmentary, as would be the case were they due to an explosion.

In drawing the sections on p. 171, it was necessary to represent them on several different scales. The smallest scale adopted was $\frac{1}{48000}$ or a quarter of an inch to 1000 feet. The dimensions of all save *a*, *b*, and *d* are based only on estimates, but these were made on the spot with all possible care, excepting *c* and *e*, where the estimates were based on photographs, and *o*, for which I had to depend on my memory. All the sketches were either made on the spot or were taken from photographs. The craters on Hualalai are designated for lack of a better system of nomenclature in the order in which we visited them from Huehue. Number 8 is the summit crater. In the description which follows, the length of 1000 feet is given in each case in inches as measured on the section.

a Tuff cone. Punch Bowl, ¼ inch.
b Tuff cone. Diamond Head, ¼ inch.
c Cinder cone on Mauna Kea, 1 inch.
d Lava pit. Kilauea, ¼ inch.
e Lava cone in Haleakala, 1 inch.
f Lava pit. Kauohi or Sixth Crater near Kilauea, ¼ inch.
g Lava cone and ring. Crater number 10 on Hualalai, 2 inches.
h Lava ring. On floor of crater number 10 on Hualalai, 8 inches.
i Lava ring on Mauna Loa, 2 inches.
j Lava bowl. Crater number 9 on Hualalai, 1 inch.
k Lava pit. Crater number 11 on Hualalai, 2 inches.
l Lava pit. Crater number 3 on Hualalai, 2 inches.
m Lava pit. Crater number 6 on Hualalai, 2 inches.
n Lava pit. Crater number 12 on Hualalai, 1 inch.
o Lava pit. Alealea or Fourth Crater near Kilauea, ¼ inch.
p Lava pit. Crater number 7 on Hualalai, 4 inches.

After the craters, among the most important features of the lava flows are the elevated formations, — the spiracles, pinnacles, and ridges. When the gases work their way up to the surface from a subterranean cavity they escape by little apertures called blow holes. In so doing they often carry small quantities of lava along with them. This lava quickly hardens on reaching the surface and builds up a tube around the aperture which we have called a spiracle. Sometimes it is closed at the top by the last escaping lava, and sometimes it is left open. These spiracles are found of all sizes, from one measuring three or four inches in diameter, up to another measuring one hundred feet. The former, found in Kilauea, was twelve inches in height, and contained a hole one inch in diameter running its whole length, except where it was closed at the top. The latter was found on Hualalai, and will be described presently.

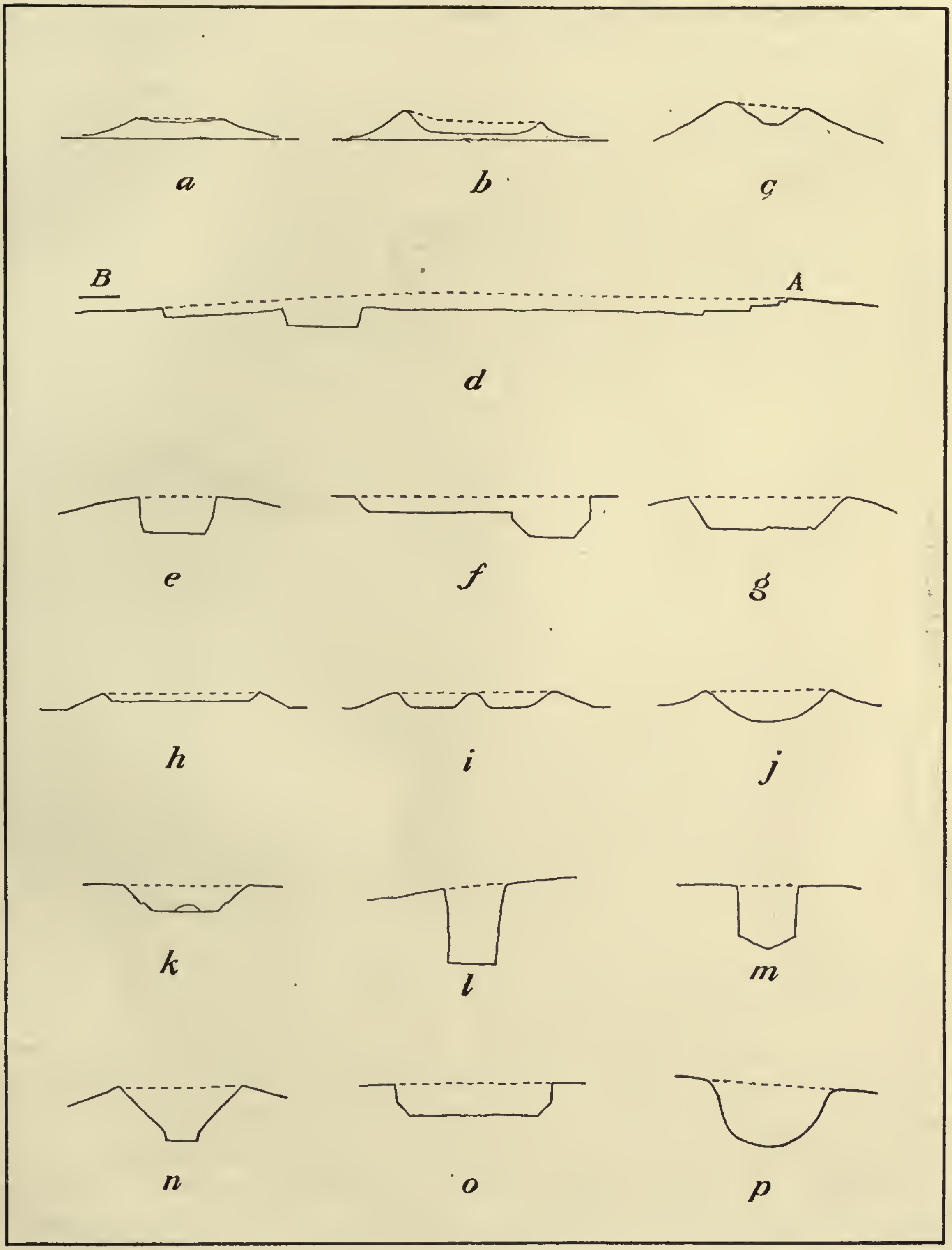
Figure 23 represents a spiracle fourteen feet in height by six feet in diameter at its base, found in Kilauea near Halemaumau. It is built up of what may be described as great drops of solidified lava. The interior tube is open at the top and measures a foot in diameter. Another somewhat smaller spiracle is seen in the background. Often several spiracles occur side by side with confluent bases, as in Figure 24. This object is also located in Kilauea, near the corral where the horses are left. It closely resembles the central peak or range of peaks so often found in the lunar craters, and is doubtless due to the same cause. See Tycho and Longomontanus, Figure 16. It is ten feet in height. Several of the spiracles forming it are open, and several are closed. There are a number of large cavities in the interior, in some of which were found some very slender lava stalactites. No lava flow had escaped from any of the craters, but two outbursts had occurred upon the side, and may be seen about half way down the slope, below the right-hand summit of the ridge.

Figure 25 shows a much larger row of spiracles found on Hualalai. They measure about a thousand feet in height above their base. Midway between the two highest summits are two smaller ones. The left hand of these is known as the Bottomless Pit. The little cone measures one hundred feet in diameter at its base by sixty feet in height. A narrow tube a few yards in diameter opens at the summit, and it is said that it has been sounded for 1400 feet without reaching bottom. Whether this figure is correct or not, doubtless the tube is very deep, and no bottom is visible. These spiracles equal in height many of the central peaks found upon the Moon.

Sometimes a row of small conical elevations, about equally spaced, occurs upon the Moon. Such a row is found in the eastern part of the floor of Wilhelm I, the large crater shown in the lower right-hand corner of Figure 16. The illustration is on too small a scale to show them to advantage, however. A row of still larger cones is found just outside and northeast of the crater. They seem like spiracles thrown up along the course of a steam crack.

Sometimes the lava slabs pile up on one another in horizontal layers, as in Figure 26, and sometimes much more irregular blocks occur, without any apparent order. These form pinnacles with very steep sides and ends. Their origin seems to be due to recent flows of lava which have transported and piled up the fragments formed from the earlier flows, somewhat as the ice pack is transported by the winds and currents in the far north. This object was found in Kilauea.

Another type of pinnacle consists of a single block of lava which may rise as high as sixty feet above the surrounding plain. The sides are often precipitous, and there



SECTIONS OF CRATERS.

is no summit crater. It is probably a solid block fallen from a neighboring cliff, that had been undermined by the liquid flow, and after floating awhile and being transported, was now frozen in, in its present position. Such a block is shown in Figure 27. It is twenty-five feet in height, and was found upon the floor of Haleakala. A second one is shown in the distance. Similar objects are of frequent occurrence upon the various *maria* of the Moon. Doubtless they are often formed as above described, but in many instances it is evident that they have been left in their original positions, while the objects formerly surrounding them have been destroyed by the flood of molten lava. Innumerable pinnacles are found upon the Mare Imbrium. A number of them are shown in Figure 28. The large crater in the photograph, near the left-hand edge, is Euler. Its diameter is nineteen miles.

A curious feature in Hawaii is the very extensive series of caves that penetrate the lava, especially the flows from Mauna Loa. Indeed, so many of them have been found that it has been suggested that they make up an appreciable part of the bulk of the mountain. A very accessible cave is situated a few miles above the town of Hilo. It is said to extend two miles up and two miles down the mountain from the entrance, which is a place where the roof happened to fall in, disclosing the cavity. The breadth of the cave is about thirty feet. Its height varies in the portion that we traversed from three to ten feet. Larger caves are found in other places, sometimes, according to Dutton, being as much as sixty or eighty feet in height, and wide in proportion. Their origin is due to the fact that the surface of the lava hardens first, and that the lower portions meanwhile flow away, leaving the cavity. Small caves occur on the floors of Kilauea and Haleakala where, since the floors are level, the formation seems to be due to the collecting of gases under sufficient pressure to hold back the lava until it has had time to solidify. Sometimes lava channels form without any roof. Some well marked channels and caves are found two or three miles north of Huehue on the Kona coast. A lava channel was noted not far from the summit of Hualalai, where the path crosses an open lava field. Another channel was found in Kilauea near Halemaumau.

At first it was thought that these lava channels were analogous to the broad grooves found upon the Moon, of which the valleys of the Alps and of Rheita are the most conspicuous examples. The Valley of Rheita is shown in Figure 31. It is 190 miles long by 15 miles wide. Several parallel valleys similar to these are found to the southwest of Pallas, and a less well marked series to the southeast of Sinus Iridum. The great range of the Altai Mountains in the southwestern quadrant of the Moon seems to form one side of such a valley constructed upon a very large scale. If so, the other side must have been destroyed by a subsequent melting, leaving an unusually smooth, light-colored surface in its place.

It was later concluded that these valleys were produced by a continuous faulting along a line of volcanic weakness, and were therefore analogous to the craters, where instead the faulting extends in all directions from a volcanic centre. The best Hawaiian representative of these grooved valleys is therefore probably the great crater of Haleakala (Figure 3), whose length measures seven miles and its breadth two. These are about the relative proportions found in many of the valleys southwest of Pallas, — nor are their dimensions so very different. The line of six small craters found in the bottom of Haleakala corresponds to the similar line of small craters found along the minute rill in the bottom of the Valley of the Alps.

The fact that often one and sometimes both ends of the lunar valleys are closed by high walls, as is the case with Haleakala, strengthens the second explanation of their origin as opposed to the earlier one. Elongated craters forming an intermediate step between the ordinary craters and the grooved valleys are of frequent occurrence upon the Moon. The largest of these is Schiller, in the southeastern quadrant. A nameless one is shown in the lower left-hand corner of Figure 31, and another in the lower right-hand corner of Figure 29. Others are shown on the border of the *mare* in the same figure.

The lunar rills may be divided into two classes, — rills and crater rills. The rills proper are extremely numerous upon the Moon. About a thousand are already known. The Ariadæus rill, shown in Figure 29, is the widest and most conspicuous of them. It measures three miles in breadth by a little over half a mile in depth, as determined by the shadows of the ridges that cross it in various places. Like all true rills its course is approximately straight, or made up of curves of long radius. In its bottom are several minute craterlets not shown in the photograph. Evidently like our dikes and mineral veins it has been partially filled from below. Other narrower rills, apparently bottomless, are found on the Moon. Two much smaller parallel rills with a north and south direction are found upon the *mare* to the left. One of these is faintly shown in the photograph. The general view that the rills are simply cracks in the lunar surface is undoubtedly correct. They occur most frequently in formations of the secondary period, that is in the dark surfaces, or if found in the primary formations, it is where the surface has apparently been softened and partially flattened out by the application of heat, as in the present instance. Rills are frequently found at the edges of the *maria* and running parallel to them, as in Serenitatis and Humorum.

A large crack is found in Kilauea in precisely this position, Figure 30. It is from 6 to 8 feet wide and from 20 to 30 feet deep near the bridge. It is said to be about a mile in length. A crack 5 to 20 feet in breadth, and 40 to 200 in depth, by 16 miles in length is located southwest of the crater, and a similar one parallel to it is found near by. Several cinder cones occur upon these cracks much as crater pits do upon the Moon. The cracks themselves have been partly filled up, but one said to be 1500 feet in depth and 5 to 15 in width is situated not far from the Sixth Crater near Kilauea.

Keanakakoi is a small crater one and a half miles southwest of Kilauea Iki. Its floor measures 500 feet in diameter and is 300 feet below the rim. It illustrates the craters having smooth floors upon the Moon. The lava surface itself is wonderfully smooth, but a close inspection shows that it has a convex surface, rising from 10 to 15 feet higher at the centre than at the edges. In this respect it also resembles what we find upon the Moon. The surface is slightly undulating, the hillocks measuring perhaps two feet in height above the depressions, thus indicating compression of the floor. The surface is also everywhere seamed with cracks, from one to three inches in breadth, and running in all directions. This indicates subsequent contraction. As often occurs upon the Moon, a crack was found running parallel to the edge of the floor, and not far from the walls. Seven prominent radial cracks were counted. The arrangement strikingly resembled that of the rills in Gassendi. A good map of this crater is given in "The Moon," by Neison, p. 337. In no place did the cracks exceed eight inches in breadth. Ferns are beginning to grow in these here and there.

A very different type of crack is sometimes produced where the surface is forced open by a subterranean lava flow, and small craters and blow holes are formed along its length. Such a one is found at Huehue, due to an eruption on the slopes of Hualalai in 1801, Figure 33. A ridge 50 feet in height in some places, and carrying on its summit a crack 30 feet wide by 40 feet deep, and extending for perhaps a mile has been produced. It is very irregular in outline.

Such a crack is represented upon the Moon in Figure 32. It is a good illustration of the crater rills so called, and is known as Bullialdus ϕ. The straight portion measures 40 miles in length by perhaps one and a half in breadth. Its edges are elevated as in its Hawaiian representative, and are quite as irregular in outline in proportion to its size. The distinction between these two types of rills is not sharply drawn upon the Moon, and the same rill sometimes exhibits both types in different portions of its length, as is the case with three small rills located on the northeastern and southeastern flanks of Copernicus, within one diameter of the crater rim. A much larger and more conspicuous crater rill occurs one and a half diameters to the northwest of Copernicus. The craterlets in this case are so distinct, however that the rill-like character is not so well marked.

Another type of depression that is found upon the Moon is known as a river-bed from its resemblance to its terrestrial analogue. Thirty-four of them have been catalogued. They have been so fully described elsewhere, Annals of the Harvard College Observatory, XXXII, 84, that it is unnecessary to more than refer to them here. The figure represents one of the larger ones. It is found on the slopes of Mt. Hadley. Its length in a straight line is 50 miles, and its maximum breadth 2000 feet. It tapers uniformly from one end to the other. In Figure 6 a marking is found closely resembling one of these river-beds. It is situated due south of Kies and west of Mercator. Its true character can only be ascertained by visual observations made under exceptionally favorable atmospheric conditions.

A favorite argument of those who deny that water ever existed upon the Moon is the statement that if such were the case, signs of erosion would be found upon its surface. In the case of the Earth, where vast bodies of water are present, these signs are very pronounced in the eroded valleys of mountain regions, and the alluvial plains of the more open country. When we search the coarser detail upon the Moon no such signs are to be found. This makes it certain that large quantities of water could never have been found upon its surface, nor indeed should we expect such to be the case considering the small value of the force of gravitation existing there. If the Moon ever possessed any water at all, it must have been in comparatively small quantities, and we should accordingly look among its finer detail for any evidence of its former existence.

Figure 34 represents Theophilus, a crater some 64 miles in diameter. The central peaks rise 5000 to 6000 feet above the crater floor, and are indented by numerous deep valleys, four being clearly shown in the photograph. It is believed that these valleys are due to erosion, and are analogous to those shown in Figure 36. This figure represents a mountain ridge just back of Honolulu, and was taken from another ridge called Tantalus. Similar valleys occur on the central peak of Eratosthenes. In the case of Copernicus they have cut so deeply that they have actually divided the central mass into three distinct mountains. The precipitation cannot have come from a general atmospheric circulation, but more likely from steam expelled from the openings of the spiracles in the central peaks themselves. The valleys seem to be flat bottomed, which would imply the action of ice rather than water. Indeed, at the present time the central peaks of Theophilus are of a dazzling brilliancy as compared with their surroundings. This, it is believed, is due to ice. The floors of both Theophilus and Copernicus show ridges that may be lateral moraines.

What we ordinarily speak of as the lunar day is twenty-nine and a half terrestrial days in length. From the standpoint of climate it may quite as properly be called the lunar year. In the latter case sunrise corresponds to spring, and sunset to autumn. The interval between them is very nearly fifteen of our days. Using the terms in this sense, we find that there are numerous spots scattered over the surface of the Moon which as the season progresses gradually darken. They reach their maximum development about or soon after midsummer, and from thence on slowly fade out and disappear with the approach of autumn. They are widely distributed over the surface, excepting near the poles, but develop most rapidly in the equatorial regions. It is believed that these variable dark spots are due to vegetation.

One of them is seen in the northern part of Julius Cæsar, the large crater just north of the Ariadæus rill, Figure 29. Others are found to the north and east of it. The summer temperature on the Moon is about that of our desert regions at midday. The winter temperature approaches absolute zero, but since grain and other seeds have been exposed without injury to the temperature of liquid air, it seems clear that even terrestrial vegetation can stand a range of temperature quite comparable to that found upon the Moon.

The central area of Figure 35 represents the crater Eratosthenes taken at the time of full moon. On the photograph it measures an inch and a quarter in diameter, and is on a scale of $\frac{1}{2000000}$, or thirty-two miles to the inch. The central peaks are pure white, and cover an area about one quarter of an inch in diameter. Northeast and northwest of them are two dark spots upon the floor, and southeast of the peaks is a very dark area lying partly on the floor and partly on the inside wall. These spots go through various interesting changes in density as the season progresses, at times entirely disappearing. In one place a slow movement of progression at the rate of four feet per hour has been noted. Outside of the crater, large dark areas are seen, which do not, however, lend themselves so readily to measurement as do those within it. Two dark lines lead away from each of the spots at the base of the central peaks. These lines are believed to be analogous to the so-called canals of Mars.

Drawings of the Moon and planets show much finer detail than it is possible to obtain by any photographs. Figure 37 is a drawing of Eratosthenes made thirty-eight hours later in the lunation than the photograph. Few changes have taken place in the meantime, and the three dark areas within the crater can be readily recognized. It will be noticed that numerous fine canals not at all visible in the photograph appear in the drawing. A much more detailed account of this crater will be found in the Annals of Harvard College Observatory, LIII, 75.

Since different observers sometimes represent the same detail by different methods of shading, and since to some eyes fine markings, like canals, appear of much less breadth than to others, it is very desirable where two drawings are to be compared, that they should both be, if possible, by the same observer. The sketch of Mars, Figure 38, was made by the writer when at the Lowell Observatory in Arizona. The similarity in appearance of the canals in these two figures, together with their variability under similar conditions, leads one to believe that they are due to the same cause, namely, vegetation.

During the summer of 1904 the writer was able to spend eight weeks at the Lowe Observatory in southern California. A considerable portion of his time was devoted to a study of Eratosthenes. The interior was found to be seamed by numerous fine cracks. Watching some of these cracks soon after the sun rose upon them, he was able to see them broaden out and change gradually into canals. It is his belief that the cracks gave out water vapor, which fertilized the vegetation along their sides and in their vicinity, and that it was the growth of this vegetation that produced the appearance of a canal.

The canals of Mars are on a much larger scale than those of the Moon; one of them indeed reaches the enormous length of 3500 miles. If they are produced naturally, the surface of the planet must be cracked in many places. It is generally thought that terrestrial volcanoes lie along subterranean cracks that do not reach the surface. The volcanoes of the great chain of the Andes lie along a straight crack reaching from southern Peru to Terra del Fuego, 2500 miles in length. The volcanoes of the Aleutian Islands lie along a curved crack equally long. Since other shorter lines of volcanoes are very numerous upon the Earth, and since countless others existed in former times, the cracks in the Earth's crust must be exceedingly numerous. Every dike and mineral vein indeed bears witness to this fact. There is no reason why terrestrial cracks should not be as numerous as those upon the Moon. In the case of the Earth they have usually been closed, sometimes by liquid matter from below, and sometimes by surface denudation. There is one crack, however, which comes to the surface in various places in eastern Asia and western Africa, and stretching from the Dead Sea to Lake Nyassa, reaches the enormous length of 3500 miles. The longest known crack upon the Moon, that of Sirsalis, measures about 400 miles.

It does not necessarily follow, however, even if both the Martian and lunar canals are due to vegetation, that the vegetation is watered in the same manner. There is certainly an atmospheric circulation upon Mars, giving rise to clouds, that might aid materially any subterranean forces. Annals of Harvard College Observatory, LIII, 155. Whether these forces could be directed intelligently by assumed intelligent inhabitants of the planet we do not know. The only argument in favor of the existence of such inhabitants is the artificial appearance of the canals. The four canals radiating from the little lake just above the centre of Figure 37 will appear to some minds quite as artificial in appearance as the four canals radiating from the elongated lake to the right of the centre of Figure 38.

To the southeast and southwest of Kilauea lies a desert region crossed in places by steam cracks. One of the first questions that I asked my guide on reaching the Volcano House was if any of these cracks were still active. He assured me that such was the case, and the next day we visited some that were near Keanakakoi. The desert was found to be absolutely barren except for certain long, narrow strips of vegetation. These consisted chiefly of ferns, some bushes, and a few trees. It was found that they grew over the steam cracks, one of which is shown in Figure 39. This particular crack was a yard in width, over two yards in depth, and about thirty yards long. If the region could have been viewed from a slight elevation we should have found a system of canals crossing the desert, these canals being due to vegetation, and differing in appearance from those found upon the Moon and Mars in no respect save size.

REFERENCE INDEX TO DESCRIPTIONS OF THE ILLUSTRATIONS.

SECTIONAL DRAWINGS ON PAGE 171.

PHOTOGRAPHS.

FIG. 1. DIAMOND HEAD

FIG. 2. CINDER CONES ON MAUNA KEA

FIG. 3. INTERIOR OF HALEAKALA

FIG. 4. MAUNA LOA

FIG 5. BULLIALDUS

FIG 6. KIES AND MERCATOR

FIG. 7. KAUHAKU. MOLOKAI

FIG. 8. SIXTH CRATER NEAR KILAUEA

FIG. 9. MOKUAWEOWEO. MAUNA LOA

FIG. 10. KILAUEA FROM WALDRON'S LEDGE

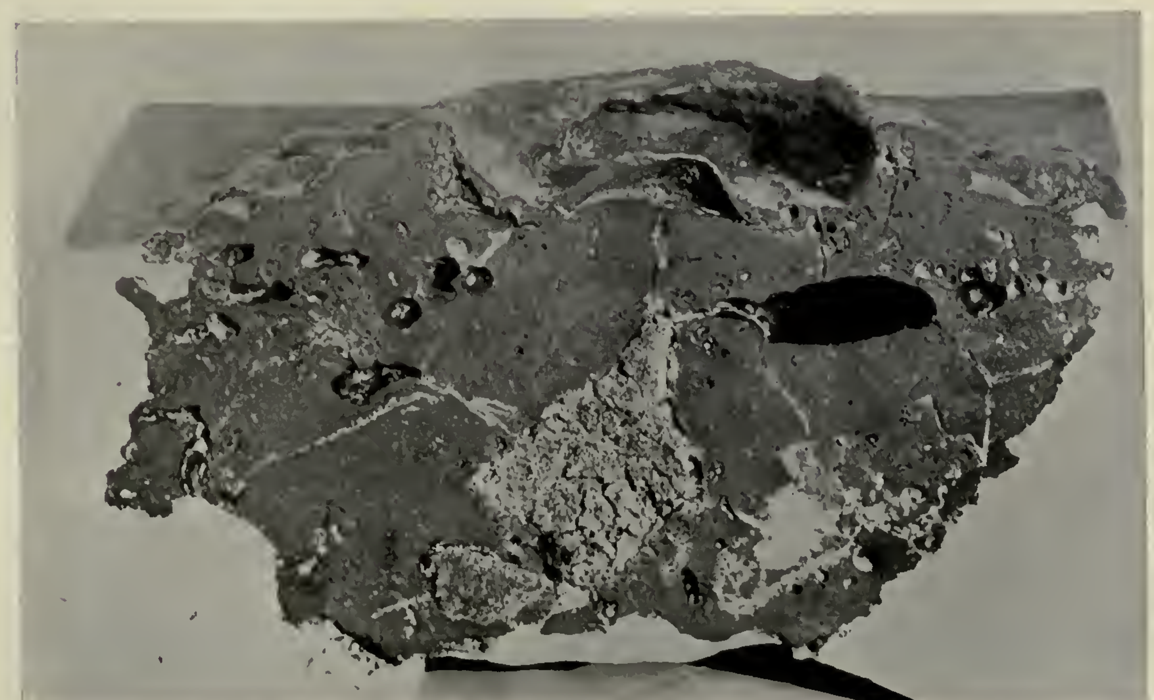


FIG. 11. SLAG SECTION

FIG. 12. LAVA LAKE IN KILAUEA

FIG. 13. LAVA LAKE IN KILAUEA

FIG. 14. SCHICKARD. PHOCYLIDES

FIG. 15. SINUS IRIDUM

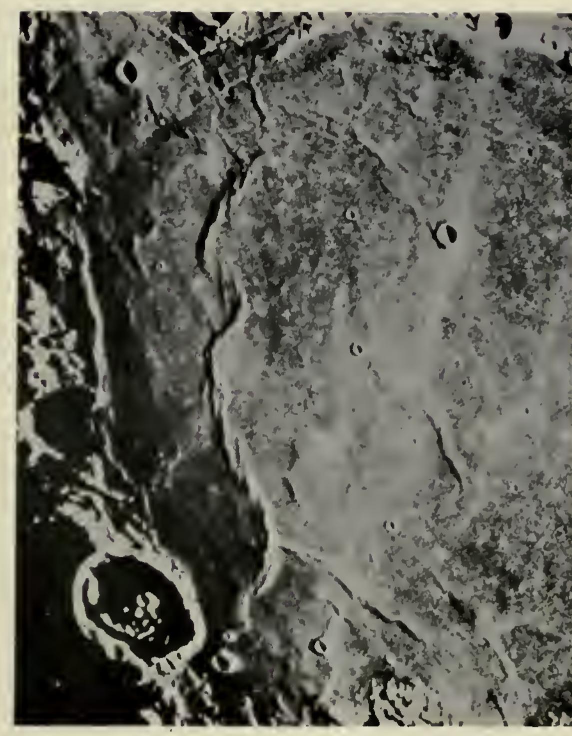


FIG. 17. RIDGES. MARE SERENITATIS

FIGURE 16 IS INVERTED.

AND HAWAIIAN PHYSICAL FEATURES

FIG. 14. SCHICKARD. PHOCYLIDES

FIG. 15. SINUS IRIDUM

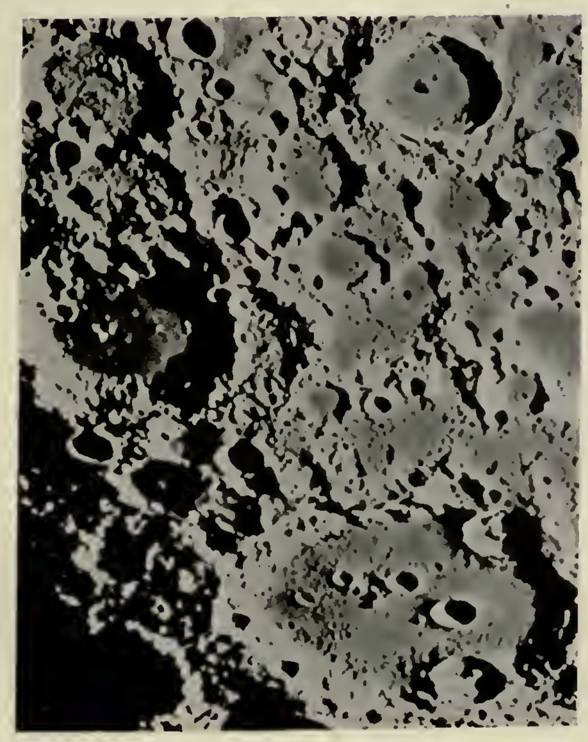


FIG. 16 CLAVIUS. LONGOMONTANUS. TYCHO

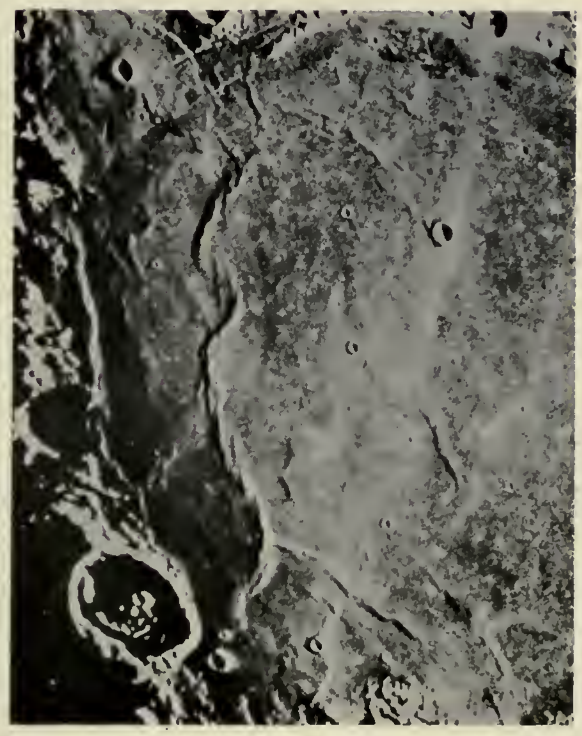


FIG. 17. RIDGES. MARE SERENITATIS

W. H. PICKERING. LUNAR AND HAWAIIAN PHYSICAL FEATURES

FIG. 18. MOKUAWEOWEO. MAUNA LOA

FIG. 19. CRATERLETS. KILAUEA IKI

FIG. 20. TOP OF CRATERLET. KILAUEA IKI

FIG. 21. CRATER PIT. KILAUEA IKI

FIG. 22. PART OF CRATER BOWL. HUALALAI

FIG. 23. SPIRACLES. KILAUEA

FIG. 24. SPIRACLES, KILAUEA

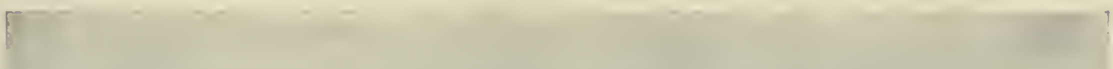


FIG. 25. SPIRACLES, HUALALAI

FIG. 26. PINNACLE. KILAUEA

FIG. 27. PINNACLE. HALEAKALA

FIG. 28. PINACLES. MARE IMBRIUM

FIG. 29. ARIADAEUS RILL

FIG. 30. CRACK. KILAUEA

FIG. 31. VALLEY OF RHEITA

FIG. 32. BULLIALDUS φ

FIG. 33. CRACK. HUEHUE

W. H. PICKERING. LUNAR AND HAWAIIAN PHYSICAL FEATURES

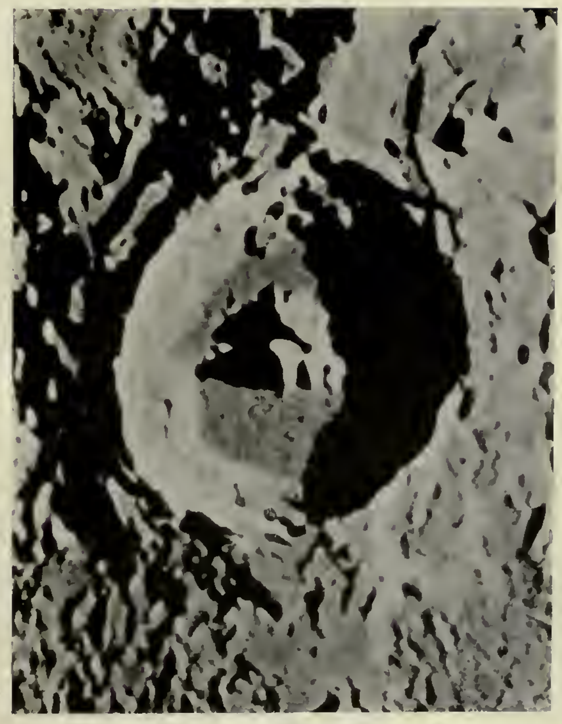


FIG. 34. THEOPHILUS

FIG. 35. ERATOSTHENES

FIG. 36. EROSION VALLEYS FROM TANTALUS. OAHU

FIG. 38. MARTIAN CANALS

FIGURE 37 IS INVERTED.

FIG. 39. TERRESTRIAL CANAL NEAR KILAUEA

FIG. 37. LUNAR CANALS

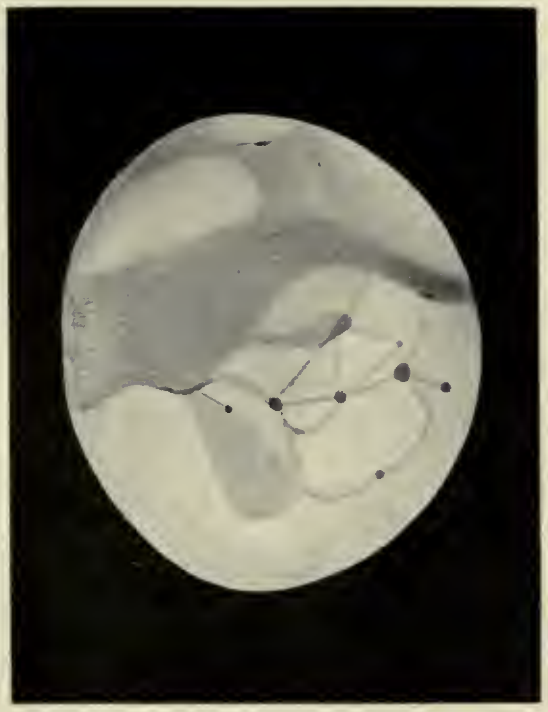


FIG. 38. MARTIAN CANALS

FIG. 39. TERRESTRIAL CANAL NEAR KILAUEA

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